Transverse momentum distributions and their forward-backward correlations in the percolating colour string approach

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The forward-backward correlations in the p_T distributions, which present a clear signature of non-linear effects in particle production, are studied in the model of percolating colour strings. Quantitative predictions are given for these correlations at SPS, RHIC and LHC energies. Interaction of strings also naturally explains the flattening of p_T distributions and increase of $\langle p_T \rangle$ with energy and atomic number for nuclear collisions.

The study of p_T distributions in hadronic and nuclear reactions at high energies offers a unique opportunity to observe non-linear effects in high-density nuclear matter. Indeed in a simple picture in which particle production goes via formation of several independent emitters, colour strings stretched between the projectile and target, the p_T distribution is independent of the number of strings and coincides with the p_T distribution from a single colour string. As a result, in this picture the observed p_T distribution does not depend on the energy nor on the atomic number of the colliding particles. Experimentally this prediction is fulfilled only in a very crude manner. In fact the average $\langle p_T \rangle$ grows with energy and also with the atomic number of the participants (the "Cronin effect"). This behaviour clearly shows that particles are produced by different strings not independently. In other words, strings interact with each other and these non-linear effects result in the experimentally observed behavior of the p_T distributions.

Some time ago the authors introduced a simple model which introduces the interaction between strings via their fusion and percolation [1,2]. In this note we study the p_T distributions in this model. We show that the model describes both qualitatively and quantatively the behaviour of the p_T distributions of the produced particles with the growth of both the energy and atomic number of the participants. We also study the forward-backward correlations (FBC) in the p_T distributions. We find that their mere existence is a signature of non-linear effects in particle production. Our model predicts a very concrete form of these correlations, which can be tested in present-day and future experiments.

We start from the particle spectra produced by a single colour string. The standard idea exploited in their description is that the observed particles are formed via quark-antiquark pair emissions by the colour field of the string. According to [3], the probability rate for this production then has a Gaussian form as a function of p_T. As soon as a $q\bar{q}$ pair is created, the colour charge Q of the string diminishes, so that at the next step the production rate is different (although also of the Gaussian form in p_T). Detailed caluclations show that the resulting $\langle p_T^2 \rangle$ of particles produced after the complete break-up of the string is proportional

to Q [4]

$$\langle p_T^2 \rangle_Q = Q \langle p_T^2 \rangle_1, \tag{1}$$

where $\langle p_T^2 \rangle_1$ is the average p_T^2 of particles produced by a "single" string, created by colour Q_0 corresponding to a single $q\bar{q}$ pair. In future we measure all colours in units Q_0, which is equivalent to putting $Q_0 = 1$. To simplify the notation we also omit the subindex T in the momentum distribution, since we shall only consider the transverse momenta.

The Gaussian distribution in p can be however theoretically supported only for infinitely high energies, which correspond to a string infinitely long in rapidity. For realistic strings with a finite length in rapidity one expects corrections due to energy conservation. Also fluctuations of the string tension may change the form of the p-distribution, as advocated in [5]. Finally an evident restriction comes at large p where the hard collision mechanism is expected to be responsible for particle creation. As a result one expects the p distribution to have a power behaved tail.

A realistic form of the p distribution corresponding to a single colour string can be extracted from the experimentally measured one in $p\bar{p}$ soft collisions at 630 and 1800 GeV/c [6]. Assuming that the effects of string interactions are small for $p\bar{p}$ interactions, we may take that the measured distribution coincides with the one for a single ordinary ($Q = 1$) string. This distribution has a form

$$w_1(p) = \frac{(k-1)(k-2)}{2\pi p_0^2} \frac{p_0^k}{(p+p_0)^k}. \tag{2}$$

Comparing the distributions at 630 and 1800 GeV and also taking into account the behaviour of the minimum bias distributions in all the energy interval from 63 to 1800 GeV [7] we parametrize

$$p_0 = 2\text{GeV/c}, \quad k = 19.7 - 0.86 \ln E, \tag{3}$$

where E is the c.m. energy in GeV. With (2) the averages $\langle p \rangle$ and $\langle p^2 \rangle$ are given by

$$p_1 \equiv \langle p \rangle_1 = p_0 \frac{2}{k-3}, \quad \langle p^2 \rangle_1 = p_0^2 \frac{6}{(k-3)(k-4)}. \tag{4}$$

Passing to the string with colour Q, to satisfy (1), we change $p_0^2 \to Q p_0^2$, so that our distribution corresponding to the string with colour Q is

$$w_Q(p) = \frac{(k-1)(k-2)}{2\pi Q p_0^2} \frac{(p_0\sqrt{Q})^k}{(p+p_0\sqrt{Q})^k}. \tag{5}$$

We stress that this distribution only refers to the soft part of the spectrum, which supposedly is generated by the string decay. The observed spectrum also contains a contribution from hard events (with a produced cluster having $p >$1.1 GeV/c, in the definition of [6]).

Our picture for the high-energy particle production consists in assuming that in the collision several colour strings are created which may overlap in the transverse space. In the overlap area the colour fields of the strings add algebraically. Due to the vector character of color charge, the resulting colour squared of the overlap area is just a sum of the colour squared of the overlapping strings. Thus in the overlap of n strings a new colour string is

formed corresponding to colour $Q_n = \sqrt{n}$. The fact that the colour of the overlapping strings is proportional to the square root of their number and not to their number has an immediate consequence of damping the multiplicities of the produced particles by a factor of the order three at the LHC energies [8]. Here we study its influence on the p-distribution.

To find the latter we have to know the distribution in the areas of overlaps of n strings, which gives the weights with which different overlaps contribute to particle production. It has been shown in [8] that in the "thermodynamic limit", that is for an idealized system with a very large total interaction area S and corresponsingly large number of strings N, the properties of the system and the overlap distribution in particular are governed by a dimensionless parameter

$$\eta = \sigma_0 \frac{N}{S} = \sigma_0 \rho. \tag{6}$$

Here σ_0 is an area of a single string and ρ the string density. Note that at $\eta > \eta_c \simeq 1.12 - 1.20$ the percolation phase transition occurs, most of the space being occupied by a single cluster formed by many overlapping strings.

It has been shown in [8] that in the thermodynamic limit the distribution in the overlaps areas with different n follows the Poisson law with an average value equal to η:

$$\lambda(n) = \frac{S_n}{S} = a(\eta) \frac{\eta^n}{n!} \tag{7}$$

with $a = \exp(-\eta)$. Here S_n is the total area in which exactly n strings overlap. Eq. (7) is valid for $n = 0, 1, 2...$, $\lambda(0)$ giving the part of the area in which there are no strings at all. Evidently the latter part does not produce particles. So we are only interested in the relative contribution to particle production of overlaps with $n = 1, 2, ...$ This will be given by (7) with a different normalization factor $a = 1/(\exp \eta - 1)$.

The overall p distribution $P(p)$ is obtained by convoluting the distribution (5) in p for fixed Q and (7) in n and taking into account that for an overlap of n strings $Q = \sqrt{n}$:

$$P(p) = \sum_{n=1} \lambda(n) w_{\sqrt{n}}(p). \tag{8}$$

As a consequence of (1) we find

$$\langle p \rangle = p_1 a(\eta) \sum_{n=1} n^{1/4} \frac{\eta^n}{n!}. \tag{9}$$

For small η this gives $\langle p \rangle / p_1 = 1 + 0.094\eta$. The behaviour of $\langle p \rangle / p_1$ for $0.5 < \eta < 4$ can also be well described by a linear dependence $1 + 0.098\eta$.

So even with a fixed average p_1 for a single string, the overall average grows with η. On the other hand, η grows both with the energy E and the atomic number A of the colliding particles [8], so that fusion of strings by itself leads to the growth of the average transverse momentum with E and A. With the distribution (2) the average p_1 also rises with energy from 0.28 GeV/c at 19.4 GeV to 0.43 GeV/c at 5500 GeV. This rise has to be combined with that due to the growth of η for collisions with nuclei. Using our earlier calculations [8] we find the values of η for central p-PB and Pb-Pb collisions at c.m. energies 19.4, 200 and 5500 GeV shown in the second and fourth columns of the Table. In the third and fifth columns we

present the corresponding values of $\langle p \rangle$ which follow from Eq (9) with the distribution (5). Comparing these values with the experiment, one should remember that they refer only to the soft part of the spectra.

The form of the p distribution in p-Pb and Pb-Pb collisons corresponding to Eq.(8) is shown in Fig. 1. With the growth of E and A the high p tail is strongly enhanced. This corresponds to the well-known Cronin effect. In Fig. 2 we present the ratio of the distributions for the p-Pb and Pb-Pb to p-p reactions. They are well compatible with the experimental ones [9].

Now we pass to the FBC in the p-distributions. They can be studied from the observation of the average p in the backward hemisphere $\langle p_B \rangle_{p_F}$ for events with given $p = p_F$ in the forward hemisphere. In absence of any interaction between colour strings (independent colour string model) the average p in both hemispheres evidently is identical with this average for a single string. Then

$$F(p_F) \equiv \langle p_B \rangle_{p_F} / p_1 = 1. \tag{10}$$

Of course, one should have in mind that correlations between different strings are imposed not only but their fusion and percolation, but also on purely kinematical grounds, due to energy conservation. However this latter effect diminishes with energy and becomes neglegible in the mid-rapidity region at large enough energy. Modulo this kinematical effect, the mere existence of FBC, that is, the difference of the right-hand side of Eq. (10) from unity is a clear signature of a dynamical interaction between strings. In our percolation string model function F can be found explicitly.

With two different observables p_B and p_F we introduce the corresponding probability $w(p_F, p_F)$ which generalizes Eq. (5) and shows the probability to find the observed particle with transverse momenta p_F and p_B in the forward and backward hemispheres. Technically it can be found from the inclusive cross-section $2Ed^3\sigma/d^3p$ integrated over the angles in the forward or backward hemispheres respectively and properly normalized. Our starting point will be an assumption that there is no correlation between emission of particles in the forward and backward hemispheres for a single string:

$$w_Q(p_F, p_B) = w_Q(p_F) w_Q(p_B), \tag{11}$$

where each of the functions w on the right-hand side is given by Eq. (5). Then for a single string of colour Q

$$\langle p_F \rangle_Q = \langle p_B \rangle_Q = \langle p \rangle_Q = \sqrt{Q} p_1. \tag{12}$$

Passing to the system of percolating strings with different overlaps we find the final distribution in p_F and p_B as a suitable generalization of (8)

$$P(p_F, p_B) = \sum_{n=1} \lambda(n) w_{\sqrt{n}}(p_F, p_B). \tag{13}$$

Integrating this expression over p_F one obtains the distribution in p_F:

$$P(p_F) = \int d^2 p_B P(p_F, p_B) = \sum_{n=1} \lambda(n) w_{\sqrt{n}}(p_F) = P(p). \tag{14}$$

As expected, it coincides with the overall distribution (8).

The conditional probability to see a particle with momentum p_B in the backward hemisphere, provided one observes a particle with momentum p_F in the forward hemispere, is given by the ratio

$$P(p_B)_{p_F} = \frac{P(p_F, p_B)}{P(p_F)}, \tag{15}$$

so that the average value of any observable $A(p_F, p_B)$ for a given fixed p_F is given by

$$\langle A \rangle_{p_F} = P^{-1}(p_F) \int d^2 p_B A(p_F, p_B) P(p_F, p_B). \tag{16}$$

Taking $A(p_F, p_B) = p_B$ we obtain for the function F in (10)

$$F(p_F) = \frac{\sum_{n=1} n^{1/4} \lambda(n) w_{\sqrt{n}}(p_F)}{\sum_{n=1} \lambda(n) w_{\sqrt{n}}(p_F)}. \tag{17}$$

Its difference from unity measures the FBC in the transverse momentum distributions.

At small η we find

$$F(p_F) = 1 + 0.0669\, \eta \frac{(1.189(p + p_0))^k}{(p + 1.189 p_0)^k}. \tag{18}$$

So positive correlations follow (as expected), which grow with the momentum from a non-zero value to saturate at a certain larger value depending on the energy (via k).

The behaviour of $F(p_F) - 1$ for the reactions p-Pb and Pb-Pb at different energies is illustrated in Fig.3. The FBC rise with energy and atomic number, their magnitude well allowing for the experimental observation.

Summarizing, we have shown that interaction of strings predicts sizable FBC in the transverse momenta, which can be tested in the forthcoming experiments. Also the dependence of the p-spectra on E and A is naturally explained for collisions with nuclei.

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Figure captions

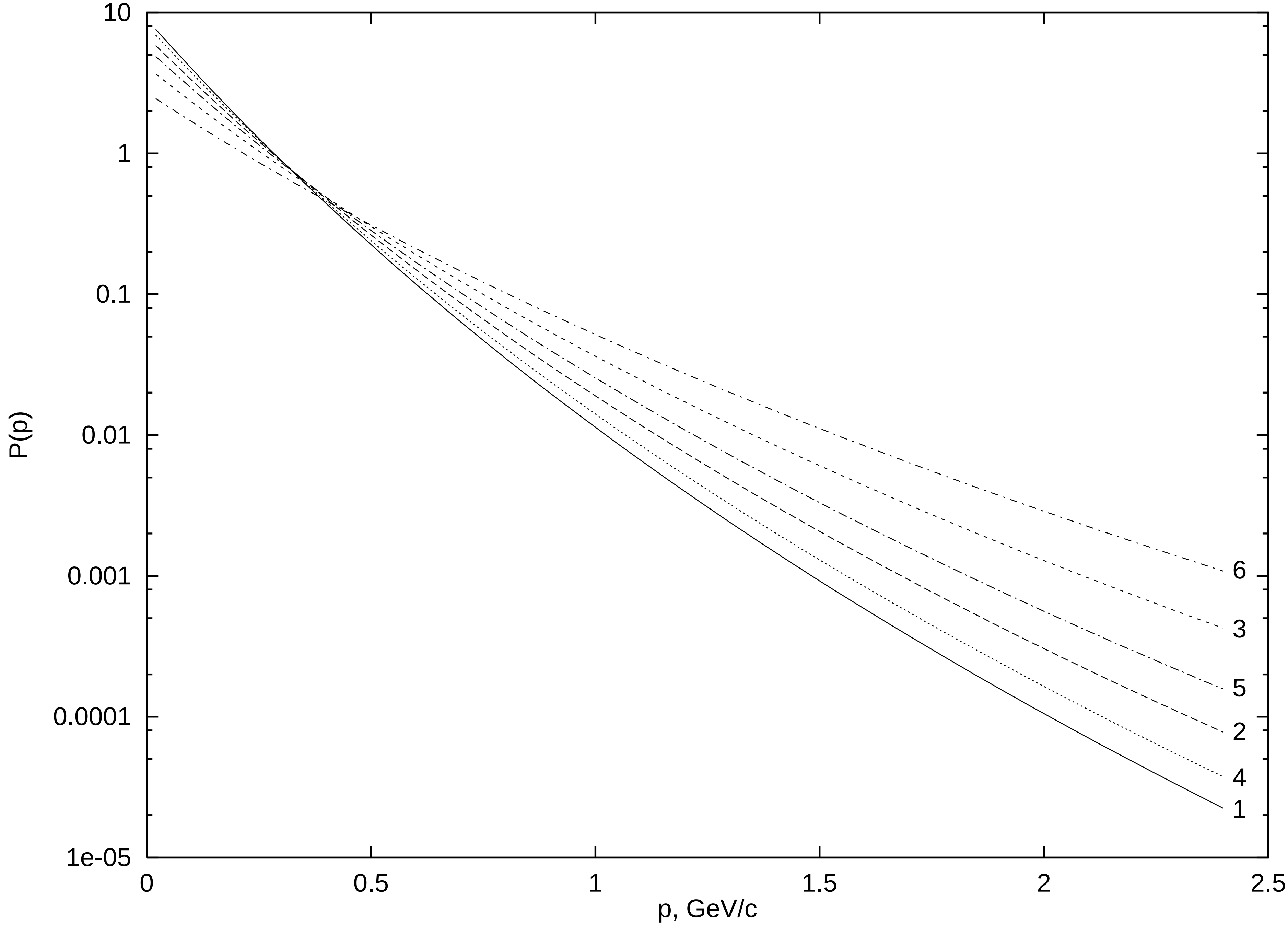
Fig. 1. Transverse momentum distributions in the reactions p-Pb and Pb-Pb at different c.m.energies (normalized to unity). Curves 1,2 and 3 correspond to p-Pb, and curves 4,5 and 6 to Pb-Pb at 19.4, 200 and 5500 GeV respectively.

Fig. 2. Ratio of p_T -distributions for the reactions p+Pb and Pb-Pb to p-p at c.m. energies 19.4, 200 and 5500 GeV. For p-Pb the curves go down with energy. For Pb-Pb the slope rises with energy

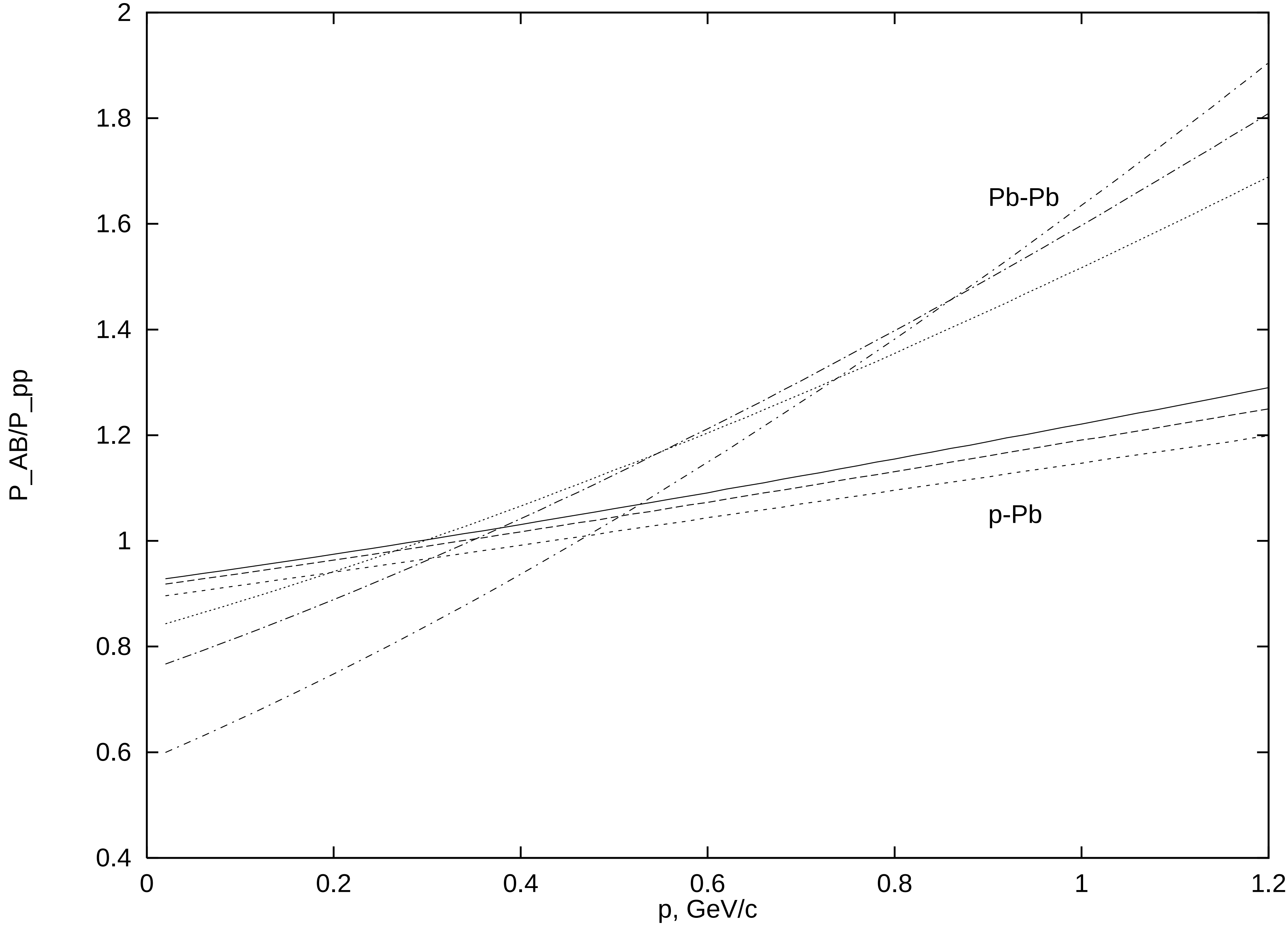
Fig. 3. The FBC parameter F-1 (Eq. (23)) as a function of p_F for the reactions p-Pb and Pb-Pb at c.m. energies 19.4, 200 and 5500 GeV. For p-P the curves rise with energy.

Table

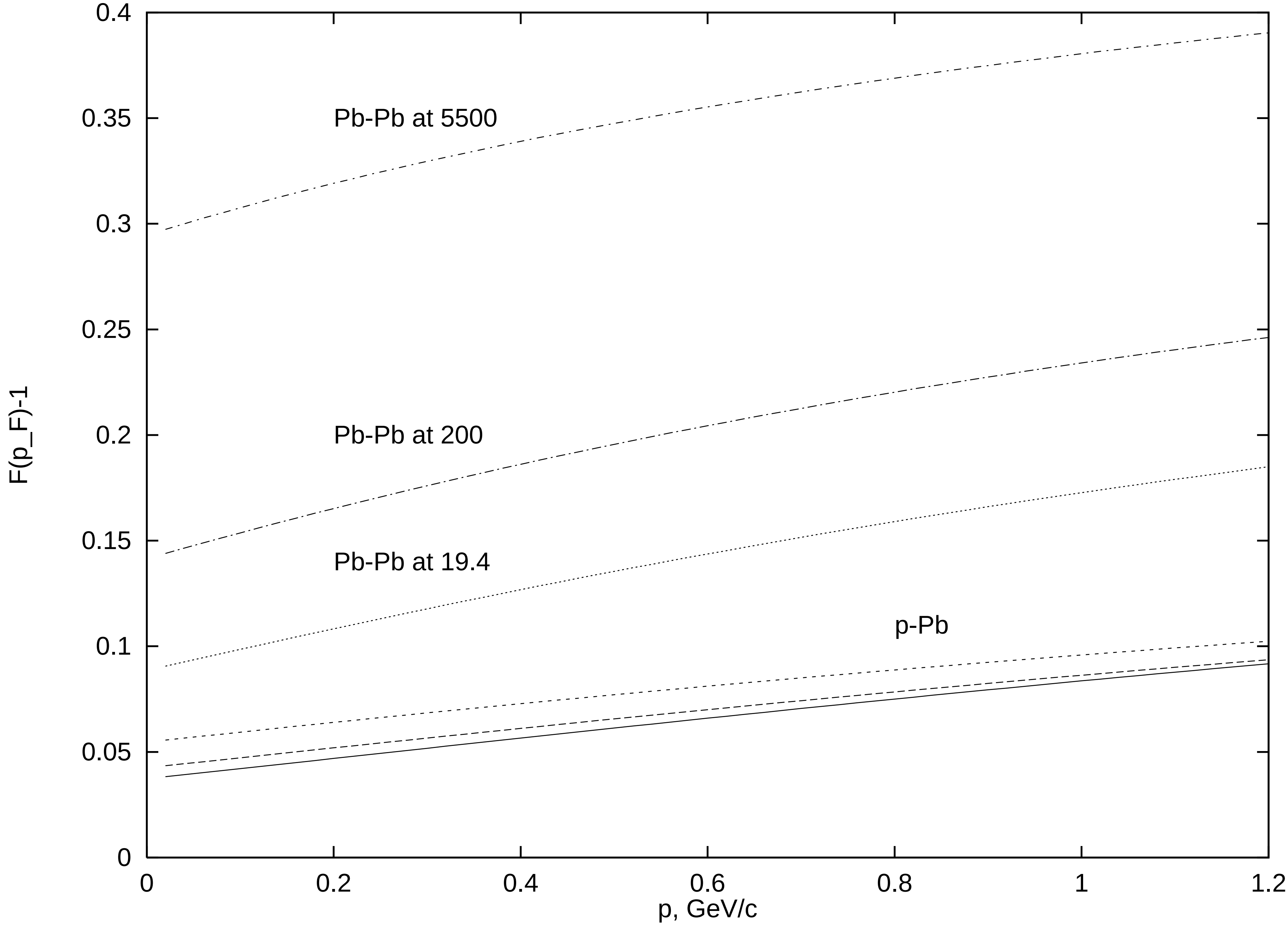
	p-Pb		Pb-Pb	
Energy (GeV)	η	$\langle p_T \rangle$ (GeV/c)	η	$\langle p_T \rangle$ (GeV/c)
19.4	0.53	0.30	1.19	0.32
200	0.60	0.35	1.82	0.39
5500	0.76	0.46	3.54	0.58



10
1
0.1
0.01
0.001
0.0001
1e-05
P(p)
0
0.5
1
1.5
2
2.5
p, GeV/c
6
3
5
2
4
1



2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0
0.2
0.4
0.6
0.8
1
1.2
P_AB/P_pp
p, GeV/c
Pb-Pb
p-Pb



0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
F(p_F)-1
Pb-Pb at 5500
Pb-Pb at 200
Pb-Pb at 19.4
p-Pb
0
0.2
0.4
0.6
0.8
1
1.2
p, GeV/c